aval Research Laboratory

ashington, DC 20375-5000

NRL Memorandum Report 6595



# Measurement of Plasma-Neutralized Super-Vacuum Currents in a Gyrotron Configuration

D. A. KIRKPATRICK*, S. H. GOLD, W.M. MANHEIMER, W.M. BLACK,
A.K. KINKEAD, D. L. HARDESTY, K. W. KILLIAN, AND M. SUCY**

*Beam Physics Branch*
*Plasma Physics Division*

**Science Applications International Corporation*
*McLean, VA 22102*

***JAYCOR, Inc.*
*Vienna, VA 22180*

February 16, 1990



Approved for public release; distribution unlimited.

SECURITY CLASSIFICATION OF THIS PAGE

# REPORT DOCUMENTATION PAGE

| | |
|---|---|
| 1a. REPORT SECURITY CLASSIFICATION<br>Unclassified | 1b. RESTRICTIVE MARKINGS |
| 2a. SECURITY CLASSIFICATION AUTHORITY | 3. DISTRIBUTION / AVAILABILITY OF REPORT<br>Approved for public release; distribution unlimited. |
| 2b. DECLASSIFICATION / DOWNGRADING SCHEDULE | |
| 4. PERFORMING ORGANIZATION REPORT NUMBER(S)<br>NRL Memorandum Report 6595 | 5. MONITORING ORGANIZATION REPORT NUMBER(S) |
| 6a. NAME OF PERFORMING ORGANIZATION<br>Naval Research Laboratory<br>6b. OFFICE SYMBOL (If applicable)<br>Code 4793 | 7a. NAME OF MONITORING ORGANIZATION |
| 6c. ADDRESS (City, State, and ZIP Code)<br>Naval Research Laboratory<br>Washington, DC 20375-5000 | 7b. ADDRESS (City, State, and ZIP Code) |
| 8a. NAME OF FUNDING / SPONSORING ORGANIZATION<br>Office of Naval Research<br>8b. OFFICE SYMBOL (If applicable) | 9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER<br>47-2797-0-0 |
| 8c. ADDRESS (City, State, and ZIP Code)<br>ONR<br>Arlington, VA 22217 | 10. SOURCE OF FUNDING NUMBERS<br>PROGRAM ELEMENT NO. \| PROJECT NO. \| TASK NO. RR011-09-4J \| WORK UNIT ACCESSION NO. |

11. TITLE (Include Security Classification)
Measurement of Plasma-Neutralized Super-Vacuum Currents in a Gyrotron Configuration

12. PERSONAL AUTHOR(S) Kirkpatrick, D.A.*, Gold, S.H., Manheimer, W.M., Black, W.M., Kinkead, A.K., Hardesty, D.L., Killian, K.W., and Sucy, M**

| 13a. TYPE OF REPORT | 13b. TIME COVERED | 14. DATE OF REPORT (Year, Month, Day) | 15. PAGE COUNT |
|---|---|---|---|
| Memorandum | FROM 2/88 TO 9/89 | 1990 February 16 | 20 |

16. SUPPLEMENTARY NOTATION
*Science Applications International Corporation, McLean, VA 22102
**JAYCOR, Inc., Vienna, VA 22180

| 17. COSATI CODES | | | 18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number) |
|---|---|---|---|
| FIELD | GROUP | SUB-GROUP | Super-Vacuum Currents; Plasma Neutralization; Gyrotron |
| | | | |

19. ABSTRACT (Continue on reverse if necessary and identify by block number)
Experimental results are reported on the transport of an electron beam with current in excess of the vacuum space-charge limited value, in a configuration directly applicable to gyrotron oscillators. The vacuum space-charge limit is circumvented by the introduction of a neutralizing background plasma which is produced by an array of four plasma guns placed immediately downstream of the electron gun anode.

| | |
|---|---|
| 20. DISTRIBUTION / AVAILABILITY OF ABSTRACT<br>☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS | 21. ABSTRACT SECURITY CLASSIFICATION<br>Unclassified |
| 22a. NAME OF RESPONSIBLE INDIVIDUAL<br>S.H. Gold | 22b. TELEPHONE (Include Area Code) (202) 767-4004 \| 22c. OFFICE SYMBOL Code 4793 |

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete. — SECURITY CLASSIFICATION OF THIS PAGE

## CONTENTS

# Measurement of Plasma-Neutralized Super-Vacuum Currents in a Gyrotron Configuration

A high power microwave device typically consists of an intense relativistic electron beam driving a beam-wave interaction in an evacuated cavity or interaction volume. This includes slow-wave devices such as backward-wave oscillators (BWO)[1,2] and relativistic klystrons, and fast-wave devices such as gyrotrons[3,4] and free-electron lasers[5,6]. A fundamental limit to the power of such devices can be obtained by multiplying their theoretical interaction efficiency by the maximum beam power that can be propagated. For a particular voltage and geometry, the maximum beam power is set by the vacuum limiting current. This limit on the beam current arises from the fact that the electron beam loses an amount of energy corresponding to the capacitive voltage drop between the electron beam and the conducting boundary.

Recently there has been much interest in exceeding the space-charge limit in high power microwave devices, notably the gyrotron and BWO[7,8,9]. The space-charge limit is severe in the gyrotron due to the nature of the gyrotron interaction, which is more favorable when the beam $\alpha$ is large ($\alpha = \beta_\perp/\beta_\parallel$, the ratio of perpendicular to parallel velocities). The space-charge limiting current for a cold annular beam of vanishing thickness is given by[10]

$$I_{L0} = I_A \frac{\gamma_0 \left[1 - (1 - \beta_{z0}^2)^{1/3}\right]^{3/2}}{2\ln(R_w/R_{beam})} \tag{1}$$

where $I_A$ is the Alfven current (17.07 kA), $\gamma_0 = 1 + (eV_0/m_0c^2)$ is the relativistic factor associated with the electron energy in the absence of any space-charge depression, $\beta_{z0} = v_{z0}/c$, $v_{z0}$ is the electron axial velocity prior to any space-charge depression, $R_w$ is the radius of the conducting boundary, and $R_{beam}$ is the radius of the electron beam. The large beam $\alpha$ which is desirable for operation of the gyrotron corresponds to low $\beta_{z0}$, and therefore low limiting currents.

One possible means to circumvent this obstacle is to use a neutral background plasma to short out the self-electric field of the electron beam. This concept of a neutralizing

Manuscript approved December 20, 1989.

background plasma has been investigated extensively in the Soviet Union[7], and has recently been the focus of some investigations with regard to the BWO[9]. In order for the background plasma to cancel the effects of the electron beam self-electric field, the density of the neutral plasma must be greater than the density of the beam electrons, so that sufficient background electrons may be expelled from the region of the transiting electron beam to provide for space-charge neutralization.

In this paper we report on the achievement of super-vacuum currents (beam currents in excess of the vacuum space-charge limit) in a configuration directly applicable to gyrotron oscillators. The experimental arrangement is shown in Fig. 1. The VEBA pulseline accelerator ($V \sim 0.6 - 2.5\,\mathrm{MV}$, $I \sim 20 - 100\,\mathrm{kA}$, $\tau \sim 60\,\mathrm{ns}$) is used to energize an electron gun which produces an annular electron beam. The electron gun consists of a hollow cylindrical cathode and an anode mask with an annular aperture. Both the cathode and the anode are fabricated from reactor-grade graphite. The annulus in the anode mask has an inner radius of 1.6 cm and and outer radius of 1.9 cm. The cathode-anode gap is 2.1 cm. Directly downstream from the anode mask is a Rogowski coil which measures the emitted beam current on each accelerator pulse. Immediately following is an array of four plasma guns[11], equally spaced in azimuth. The plasma guns are individually energized by an array of four $0.22\,\mu\mathrm{F}$ capacitors which are typically charged to 14 kV. The entire system is immersed in a uniform 10 kG axial guide magnetic field, produced by an external solenoid. In addition, as shown in Fig. 1, there is a field reversed, thin-solenoid "dip" magnet which is used to spin up the electron beam[12], and a Helmholtz pair positioned symmetrically about the cavity region. In these experiments the cavity region is composed of a simple straight wall drift space. The magnetic field in the center of the cavity region is 29 kG.

The plasma density produced in the cavity region has been characterized by 70 GHz quadrature microwave interferometry and by time-integrated photography of the light emitted by the plasma. The photographs of the light emitted by the plasma in the cavity region indicate that while the plasma is relatively uniform in the azimuthal direction, significant

non-uniformity exists in the radial direction, with the peak density being close to the cavity wall. Close inspection of the interferometry data shows the presence of cutoff-level densities early in the plasma pulse, when the line-averaged plasma density is computed to be about $10^{13}\,\mathrm{cm}^{-3}$. Since the plasma cutoff for our 70 GHz interferometer occurs at $n_p = 6 \times 10^{13}\mathrm{cm}^{-3}$, this would suggest peak densities on the order of a factor of five greater than the line averaged densities. The data presented here are obtained with line-averaged plasma densities in the range $1.5 - 5 \times 10^{11}\,\mathrm{cm}^{-3}$, corresponding to peak background plasma densities in the range $0.8 - 3 \times 10^{12}\,\mathrm{cm}^{-3}$.

The achievement of super-vacuum currents is demonstrated by measuring the beam current transported through the cavity region with and without the background neutralizing plasma, while varying the amplitude of the "dip" magnet. This data is shown in Fig. 2(a), where we plot the measured cavity current against the amplitude of the "dip" magnet for both the vacuum and plasma-neutralized cases. For the plasma-neutralized case the data represent the maximum measured signals across a sample of neutral plasma densities. This step is necessary because with too little plasma background the beam is not neutralized, while with too much plasma background the beam current is partially neutralized and the Rogowski measurement gives an artificially low account of the beam current. Similarly, as the "dip" magnitude increases the average beam axial velocity decreases, which results in an increase in the local number density of beam electrons. The higher number density of beam electrons requires a greater background plasma density to provide for neutralization. The variation of the plasma density is achieved by varying the time delay between the firing of the plasma guns and the firing of the accelerator. For our measured beam parameters, and using the estimated beam alpha, the peak number density of the beam electrons is in the range $1 - 3 \times 10^{12}\,\mathrm{cm}^{-3}$. Combined with our previous estimate of the relative non-uniformity of the neutral background plasma, the condition for neutralization of $n_b \approx n_p$ appears to be well met.

The variation of $\alpha$ with the amplitude of the dip magnet is shown in Fig. 2(b). Here

we plot the average and spread in $\alpha$ for the calculated trajectories of an ensemble of non-interacting particles, using the measured magnetic fields and electron beam voltage. The calculated transmitted current for these single particle ensembles is shown in Fig. 2(a) as the "mirror limiting current". In this case, the loss of current is due wholly to mirroring of individual particles in the region of the magnetic compression. It can be seen that there is good agreement between this curve and the measured data for the plasma neutralized case. Similarly, we can use the calculated beam alpha to calculate space-charge limiting current for a zero-temperature beam of non-zero thickness[10], and the space-charge limiting current for a zero-thickness beam with a non-zero thermal spread in velocity[13]. These curves are shown in Fig. 2(a) as $I_{SC}(\Delta r)$ and $I_{SC}(\Delta\alpha)$, respectively. Both curves are seen to agree reasonably well with the measured data for the vacuum case. It should be noted that for pump amplitudes corresponding to an average beam $\alpha$ of 1 to 2, the presence of the neutralizing plasma results in an increase in the beam current propagated through the cavity by a factor of about three.

The calculations of $I_{SC}(\Delta r)$, $I_{SC}(\Delta\alpha)$, and the mirror limiting current shown in Fig. 2(a) are obtained using a very simple electron beam distribution function. The inner and outer radii of the electron beam correspond to the inner and outer radii of the anode mask aperture. The velocity distribution assumes a uniform spread in initial diode $\alpha$ ranging from 0 to 0.1. This range gave good agreement for both the roll-over point of the mirror limiting current, and for the space-charge limited current in the case of no pump field. Deviations of the theoretical curves from the data, for both the vacuum and plasma-neutralized cases, are probably due to the details the electron beam distribution function which are grossly simplified in the calculations. Further, no accounting has been made of the possibility of diamagnetic effects associated with the high-$\alpha$ beam, nor do the calculations consider the effect of space charge on the "spinning up" of the electron beam by the pump magnet.

In conclusion, we have demonstrated transport of beam currents in excess of the vacuum space-charge limit in a plasma-filled, gyrotron type cavity. For values of the beam alpha in

the range of 1 to 2 the increase in electron beam current is approximately a factor of three. Comparison of the measured transmitted vacuum current with the theoretical vacuum space-charge limited current shows good agreement. In the case of the plasma neutralized measurements, we obtain good agreement from a simple calculation of magnetic mirroring of an ensemble of non-interacting electrons, where the ensemble is taken to represent a uniform, low initial temperature, annular beam of radial dimensions given by the anode mask. The higher intra-cavity beam currents achieved with the aid of the neutralizing background plasma should enable higher power operation in existing intense beam gyrotron designs[14].

## Acknowledgments

The authors would like to acknowledge the assistance of B. Weber of NRL with the use of the plasma guns, setup of the microwave interferometry, and associated data analysis programs. This work was supported by the Office of Naval Research.

# References


[1] Y. Carmel *et al.*, Phys. Rev. Lett. **33**, 1278 (1974).

[2] N. Kovalev *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **18**, 232 (1973) [JETP Lett. **18**, 138 (1973)].

[3] V.L. Granatstein, Int. J. Electron. **57**, 787 (1984).

[4] S.P. Bugaev *et al.*, Pis'ma Zh. Tekh. Fiz. **9**, 1385 (1983) [Sov. Tech. Phys. Lett. **9**, 596 (1983)].

[5] J. Fajans *et al.*, Phys. Fluids **28**, 1995 (1985).

[6] T.J. Orzechowski *et al.*, Phys. Rev. Lett. **54**, 889 (1985).

[7] M.V. Kuzelev *et al.*, Fiz. Plazmy **13**, 1370 (1987) [Sov. J. Plasma Phys. **13**, 793 (1987)].

[8] V.I. Kurilko *et al.*, Zh. Tekh. Fiz. **51**, 1415 (1981) [Sov. Phys. Tech. Phys. **26**, 812 (1981)].

[9] Y. Carmel *et al.*, Phys. Rev. Lett. **62**, 2389 (1989).

[10] A.K. Ganguly and K.R. Chu, Int. J. Infrared Millimeter Waves **5**, 103 (1984).

[11] R.J. Commisso *et al.*, NRL Memo Report 6057, Naval Research Laboratory, Wash. DC 20375-5000 (1987).

[12] S.H. Gold *et al.*, Phys. Fluids **30**, 2226 (1987).

[13] T. Antonsen and B. Levush, Int. J. Electron. **61**, 871 (1986)

[14] W.M. Black *et al.*, Phys. Fluids B **2**, 193 (1990).

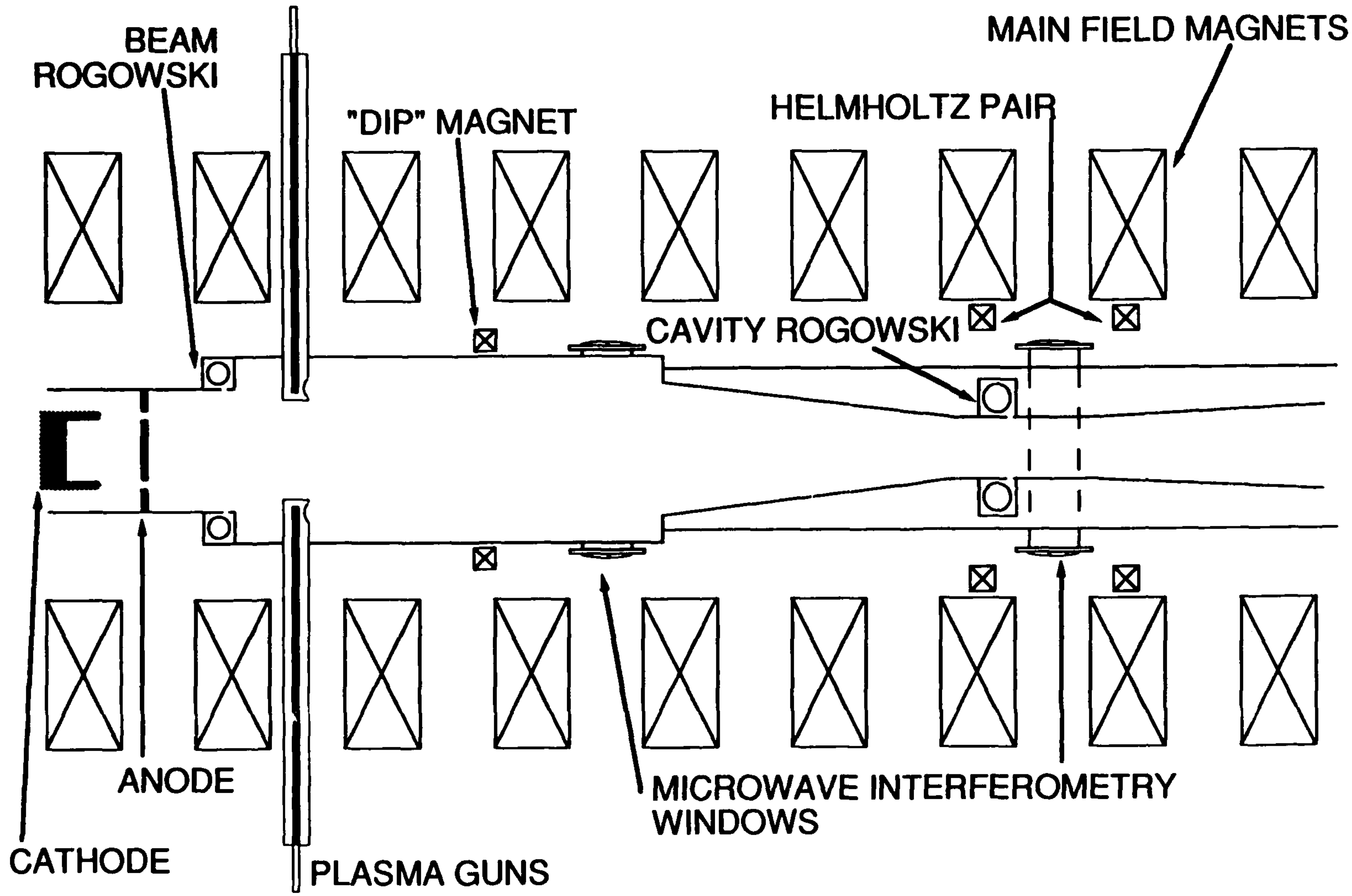


Fig. 1. The schematic layout of the VEBA plasma-neutralized gyrotron experiment, showing the magnet positions, inner conducting wall, vacuum chamber, microwave interferometry windows, plasma guns, and cathode-anode positions.

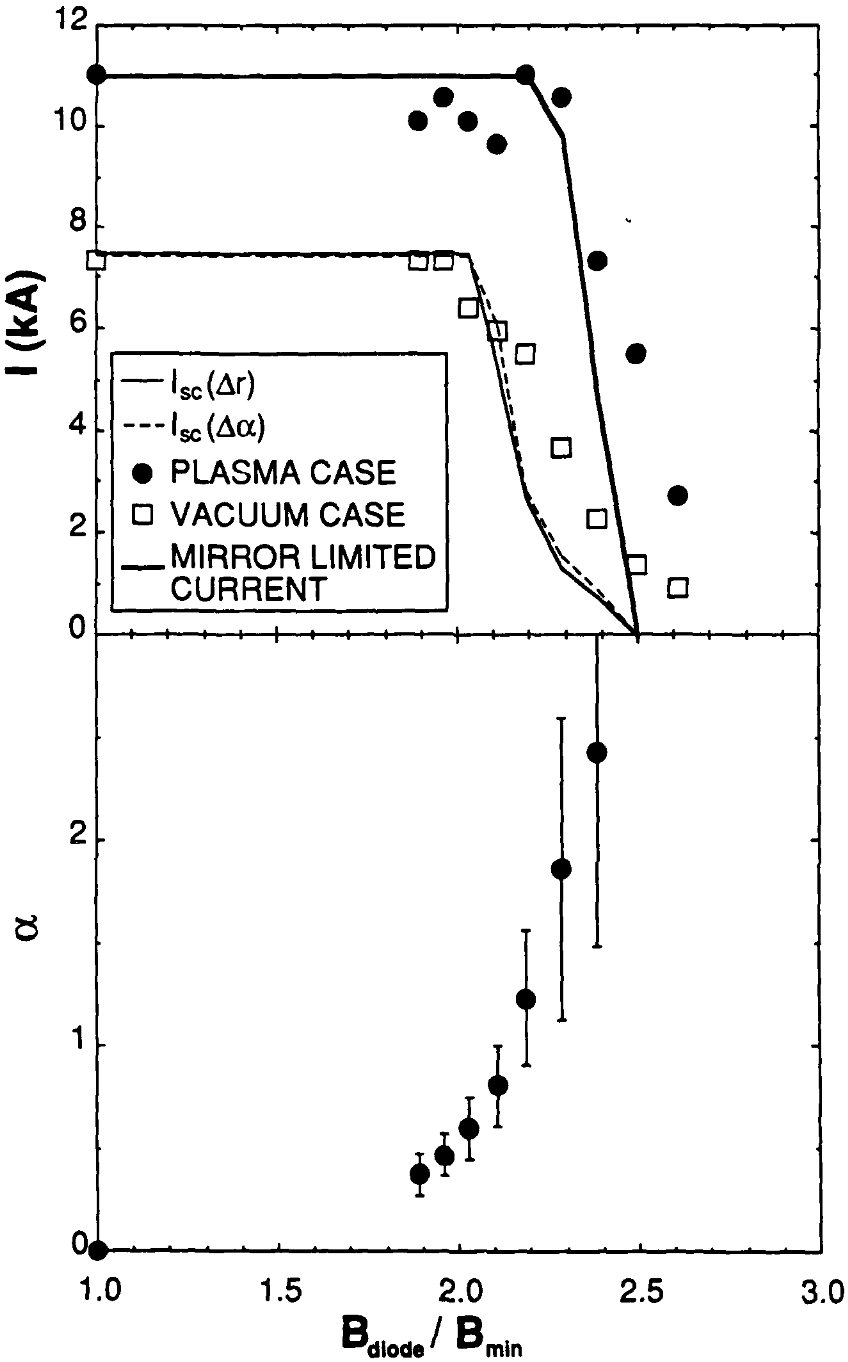


Fig. 2. The current measured by the Rogowski coil positioned in the cavity region, for the vacuum case (open circles) and for the plasma-neutralized case (solid circles), shown with the calculated vacuum space-charge limiting current for a beam of non-zero thickness (dotted line), the calculated vacuum space-charge limiting current for a beam with non-zero thermal spread (thin line), and the calculated transmitted current for an ensemble of non-interacting electrons (bold line).

## 4793/4 DISTRIBUTION LIST

| | |
|---|---|
| Air Force Avionics Laboratory<br>AFWAL/AADM-1<br>Wright/Patterson AFB, OH 45433<br>Attn: Walter Friez | 1 copy |
| Air Force Office of Scientific Research<br>Bolling AFB<br>Washington, D.C. 20332<br>Attn: H. Schlossberg | 1 copy |
| Air Force Weapons Lab<br>Kirkland AFB<br>Albuquerque, NM 87117<br>Attn: Dr. William Baker | 2 copies |
| Dr. A.H. Guenter | 1 copy |
| Bhabha Atomic Research Center<br>Laser Division<br>Bombay, India 400085<br>Attn: T.S. Shirsat | 1 copy |
| Columbia University<br>520 West 120th Street<br>Department of Electrical Engineering<br>New York, NY 10027<br>Attn: Dr. S.P. Schlesinger | 1 copy |
| A. Sen | 1 copy |
| Columbia University<br>520 West 120th Street<br>Department of Applied Physics<br>and Nuclear Engineering<br>New York, NY 10027<br>Attn: T.C. Marshall | 1 copy |
| R. Gross | 1 copy |
| Cornell University<br>School of Applied and Engineering Physics<br>Ithica, NY 14853<br>Attn: Prof. Hans H. Fleischmann | 1 copy |
| John Nation | 1 copy |
| R. N. Sudan | 1 copy |
| Creol-FEL Research Pavillion<br>12424 Research Parkway, Suite 400<br>Orlando, FL 32826<br>Attn: Dr. Luis R. Elias | 1 copy |
| Dr. I. Kimel | 1 copy |

| | |
|---|---|
| Dartmouth College<br>18 Wilder, Box 6127<br>Hanover, NH 03755<br>Attn: Dr. John E. Walsh | 1 copy |
| Defense Advanced Research Project Agency/DEO<br>1400 Wilson Blvd.<br>Arlington, VA 22209<br>Attn: Dr. L. Buchanan | 1 copy |
| Defense Communications Agency<br>Washington, D.C. 20305<br>Attn: Dr. Pravin C. Jain<br>Assistant for Communications Technology | 1 copy |
| Defense Nuclear Agency<br>Washington, D.C. 20305<br>Attn: Mr. J. Farber | 1 copy |
| Dr. Leon Wittwer (RAAE) | 5 copies |
| Defense Technical Information Center<br>Cameron Station<br>5010 Duke Street<br>Alexandria, VA 22314 | 2 copies |
| Department of Energy<br>Div. of Advanced Energy Projects<br>Washington, DC 20545<br>Attn: Dr. R. Gajewski | 1 copy |
| Department of Energy<br>Office of Energy Research<br>Washington, D.C. 20545<br>Attn: C. Finfgeld/ER-542, GTN | 1 copy |
| T.V. George/ER-531, GTN | 1 copy |
| D. Crandall/ER-54, GTN | 1 copy |
| Dr. David F. Sutter/ER-224, GTN | 1 copy |
| Director of Research<br>U. S. Naval Academy<br>Annapolis, MD 21402-5021 | 1 copy |
| General Atomics<br>13-260<br>Box 85608<br>San Diego, CA 92138<br>ATTN: Dr. J. Doane | 1 copy |
| Dr. C. Moeller | 1 copy |

Georgia Tech. EES-EOD
Baker Building
Atlanta, GA 30332
Attn: Dr. James J. Gallagher — 1 copy

Hanscomb Air Force Base
Stop 21, MA 01731
Attn: Lt. Rich Nielson/ESD/INK — 1 copy

Hughes Aircraft Co.
Electron Dynamics Division
3100 West Lomita Boulevard
Torrance, CA 90509
Attn: J. Christiansen — 1 copy
J. Tancredi — 1 copy

Hughes Research Laboratory
3011 Malibu Canyon Road
Malibu, CA 90265
Attn: Dr. R. Harvey — 1 copy
Dr. R.W. Schumacher — 1 copy

KMS Fusion, Inc.
3941 Research Park Dr.
P.O. Box 1567
Ann Arbor, MI 48106
Attn: S.B. Segall — 1 copy

Lawrence Berkeley Laboratory
University of California
1 Cyclotron road
Berkeley, CA 94720
Attn: Dr. A.M. Sessler — 1 copy

Lawrence Livermore National Laboratory
P.O. Box 808
Livermore, CA 94550
Attn: Dr. D. Prosnitz — 1 copy
Dr. T.J. Orzechowski — 1 copy
Dr. J. Chase — 1 copy
Dr. W.A. Barletta — 1 copy
Dr. D.L. Birx — 1 copy
[redacted] — [redacted]
Dr. E.T. Scharlemann — 1 copy

Litton Electron Devices
960 Industrial Road
San Carlos, CA 94070
Attn: Library — 1 copy

Los Alamos National Scientific Laboratroy
P.O. Box 1663, MSJ 564
Los Alamos, NM 87545
Attn: Dr. Brian Newman 1 copy

Los Alamos Scientific Laboratory
P.O. Box 1663, AT5-827
Los Alamos, NM 87545
Attn: Dr. T.J.T. Kwan 1 copy
Dr. L. Thode 1 copy
[redacted] [redacted]
Dr. R. R. Bartsch 1 copy

Massachusetts Institute of Technology
Department of Physics
Cambridge, MA 02139
Attn: Dr. G. Bekefi/36-213 1 copy
Dr. M. Porkolab/NW 36-213 1 copy
Dr. R. Davidson/NW 16-206 1 copy
Dr. A. Bers/NW 38-260 1 copy
Dr. K. Kreischer 1 copy
Dr. B. Danby 1 copy
Dr. G.L. Johnston 1 copy

Massachusetts Institute of Technology
167 Albany St., N.W. 16-200
Cambridge, MA 02139
Attn: Dr. R. Temkin/NW 14-4107 1 copy

Mission Research Corporation
8560 Cinderbed Road, Suite 700
Newington, VA 22122
Attn: Dr. M. Bollen 1 copy
Dr. Tom Hargreaves 1 copy
Dr. J. Pasour 1 copy

Naval Research Laboratory
Addressee: Attn: Name/Code
Code 0124 - ONR 1 copy
Code 1000 - Commanding Officer 1 copy
Code 1001 - T. Coffey 1 copy
Code 1003.9A - Computer Resources Architect 1 copy
Code 1005 - Head, Office of Mgt. & Admin. 1 copy
Code 1005.1 - Deputy Head, Off. of Mgt. & Admin. 1 copy
Code 1005.6 - Head, Directives Staff 1 copy
Code 1200 - Capt. [redacted] R.W. Michaux 1 copy
Code 1201 - Deputy Head, Command Support Division 1 copy
Code 1220 - Security 1 copy
Code 2000 - J. Brown 1 copy
Code 2604 - NRL Historian 1 copy
Code 2628 - TID Distribution 22 copies
Code 2634 - Cindy Sims 1 copy
Code 3000 - R. Doak 1 copy

| | |
|---|---|
| Code 4000 - W. Ellis | 1 copy |
| Code 4000 - D. Nagel | 1 copy |
| Code 4700 - S. Ossakow | 26 copies |
| Code 4700.1 - A. Ali | 1 copy |
| Code 4790 - Branch Office | 25 copies |
| Code 4790 - W. Black | 1 copy |
| Code 4790 - G. Cooperstein | 1 copy |
| Code 4790 - A. Fliflet | 1 copy |
| Code 4790 - S. Gold | 1 copy |
| Code 4790 - C. Hui | 1 copy |
| Code 4790 - C. Kapetanakos | 1 copy |
| Code 4790 - A. Kinkead | 1 copy |
| Code 4790 - Y. Lau | 1 copy |
| Code 4790 - W. Manheimer | 1 copy |
| Code 4790 - M. Rhinewine | 1 copy |
| Code 4790 - P. Sprangle | 1 copy |
| Code 5700 - L. Cosby | 1 copy |
| Code 6840 - S. Ahn | 1 copy |
| Code 6840 - A. Ganguly | 1 copy |
| Code 6840 - R. Parker | 1 copy |
| Code 6840 - N. Vanderplaats | 1 copy |
| Code 6850 - L. Whicker | 1 copy |
| Code 6875 - R. Wagner | 1 copy |

Naval Sea Systems Command
Department of the Navy
Washington, D.C. 20362
Attn: Commander, PMS 405-300 — 1 copy

Northrop Corporation
Defense Systems Division
600 Hicks Rd.
Rolling Meadows, IL 60008
Attn: Dr. Gunter Dohler — 1 copy

Oak Ridge National Laboratory
P.O. Box Y
Mail Stop 3
Building 9201-2
Oak Ridge, TN 37830
Attn: Dr. A. England — 1 copy

Office of Naval Research
800 N. Quincy Street
Arlington, VA 22217
Attn: Dr. C. Roberson — 1 copy

Office of Naval Research
1012 W 36th Street, Childs Way Bldg.
Los Angeles, CA 90089-1022
Attn: Dr. R. Behringer — 1 Copy

Optical Sciences Center
University of Arizona
Tucson, AZ 85721
Attn: Dr. Willis E. Lamb, Jr. — 1 copy

Physical Science Inc.
603 King Street
Alexandria, VA 22314
ATTN: M. Read — 1 copy

Physics International
2700 Merced Street
San Leandro, CA 94577
Attn: Dr. J. Benford — 1 copy

Princeton Plasma
Plasma Physics Laboratory
James Forrestal Campus
P.O. Box 451
Princeton, NJ 08544

| | |
|---|---|
| Attn: Dr. H. Hsuan | 2 copies |
| Dr. D. Ignat | 1 copy |
| Dr. H. Furth | 1 copy |
| Dr. P. Efthimion | 1 copy |
| Dr. F. Perkins | 1 copy |

Raytheon Company
Microwave Power Tube Division
Foundry Avenue
Waltham, MA 02154
Attn: N. Dionne — 1 copy

Sandia National Laboratories
ORG. 1231, P.O. Box 5800
Albuquerque, NM 87185

| | |
|---|---|
| Attn: Dr. Thomas P. Wright | 1 copy |
| Mr. J.E. Powell | 1 copy |
| Dr. J. Hoffman | 1 copy |
| Dr. W.P. Ballard | 1 copy |
| Dr. C. Clark | 1 copy |

Science Applications, Inc.
1710 Goodridge Dr.
McLean, VA 22102

| | |
|---|---|
| Attn: Adam Drobot | 1 copy |
| P. Vitello | 1 copy |
| D. Bacon | 1 copy |
| C. Menyuk | 1 copy |

Science Research Laboratory
15 Ward Street
Somerville, MA 02143
Attn: Dr. R. Shefer — 1 copy

SPAWAR
Washington, D.C. 20363
Attn: E. Warden, Code PDE 106-3113 — 1 copy
Capt. Fontana, PMW 145 — 1 copy

Spectra Technologies
2755 Northup Way
Bellevue, WA 98004
Attn: Dr. J.M. Slater — 1 copy

Stanford University
Dept. of Electrical Engineering
Stanford, CA 94305
Attn: Dr. J. Feinstein — 1 copy

Stanford University
High Energy Physics Laboratory
Stanford, CA 94305
Attn: Dr. T.I. Smith — 1 copy

Stanford University
SLAC
Stanford, CA 94305
Attn: Dr. Jean Labacqz — 1 copy

TRW, Inc.
One Space Park
Redondo Beach, CA 90278
Attn: Dr. H. Boehmer — 1 copy
Dr. T. Romisser — 1 copy
Dr. Z. Guiragossian — 1 copy

University of California
Physics Department
Irvine, CA 92717
Attn: Dr. G. Benford — 1 copy
Dr. N. Rostoker — 1 copy

University of California
Department of Physics
Los Angeles, CA 90024
Attn: Dr. A.T. Lin — 1 copy
Dr. N. Luhmann — 1 copy
Dr. D. McDermott — 1 copy

University of Maryland
Department of Electrical Engineering
College Park, MD 20742
Attn: Dr. V. L. Granatstein — 1 copy
Dr. W. W. Destler — 1 copy

University of Maryland
Laboratory for Plasma and Fusion
Energy Studies
College Park, MD 20742

| | |
|---|---|
| Attn: Dr. Tom Antonsen | 1 copy |
| Dr. John Finn | 1 copy |
| Dr. Jhan Varyan Hellman | 1 copy |
| Dr. W. Lawson | 1 copy |
| Dr. Baruch Levush | 1 copy |
| Dr. Edward Ott | 1 copy |
| Dr. M. Reiser | 1 copy |

University of New Mexico
Department of Physics and Astronomy
800 Yale Blvd, N.E.
Albuquerque, NM 87131

| | |
|---|---|
| Attn: Dr. Gerald T. Moore | 1 copy |

University of Tennessee
Dept. of Electrical Engr.
Knoxville, TN 37916

| | |
|---|---|
| Attn: Dr. I. Alexeff | 1 copy |

University of Utah
Department of Electrical Engineering
3053 Merrill Engineering Bldg.
Salt Lake City, UT 84112

| | |
|---|---|
| Attn: Dr. Larry Barnett | 1 copy |
| Dr. J. Mark Baird | 1 copy |

U. S. Army
Harry Diamond Labs
2800 Powder Mill Road
Adelphi, MD 20783-1145

| | |
|---|---|
| Attn: Dr. Howard Brandt | 1 copy |
| Dr. Edward Brown | 1 copy |
| Dr. Stuart Graybill | 1 copy |
| Dr. A. Kehs | 1 copy |
| Dr. J. Silverstein | 1 copy |

Varian Associates
611 Hansen Way
Palo Alto, CA 94303

| | |
|---|---|
| Attn: Dr. H. Huey | 1 copy |
| Dr. H. Jory | 1 copy |
| Dr. Kevin Felch | 1 copy |
| Dr. R. Pendleton | 1 copy |
| Dr. A. Salop | 1 copy |

Varian Eimac San Carlos Division
301 Industrial Way
San Carlos, CA 94070

| | |
|---|---|
| Attn: C. Marshall Loring | 1 copy |

WL/CA
Kirtland AFB, NM 87117-6008
Attn: Mr. Brendan B. Godfrey 1 copy

Yale University
Applied Physics
Madison Lab
P.O. Box 2159
Yale Station
New Haven, CN 06520
Attn: Dr. I. Bernstein 1 copy

Ken Busby 1 copy